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MODELLING OF DIRECT SELF CONTROL USED IN ELECTRICAL TRACTION

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Abstract **– In the paper it is presented the DSC mathematical modelling used on the locomotives with traction induction motor. They are built the associated structural diagrams of those three configuration of DSC, which they permit a fast implementation into a simulation soft. By means of these models they are achieved simulations which they permit the validation of the mathematical models. Models can be used as such or with certain simplifications into a more complex associated construction of the study through simulation of the locomotives end electrical trains.**

Keywords: *Direct Self Control, modelling, electric traction, structural diagrams.*

1. INTRODUCTION

The **D**irect **S**elf **C**ontrol (DSC), invented by Depenbrock [2], represents a method, used for the control of voltage-source inverter – traction induction motor ensemble. In the control strategy case of the voltage-source inverter and traction induction motor, it is desired like, through the adequate command of the voltage-source inverter it can obtain any variation curve of the currents and voltages of the traction induction motor. In fact, the used inverters majorities in the high speed traction, because of the restricted switching frequency of semiconductor elements (200…300 Hz), they can produce only 7 discrete space vector values of these variables [2], [5] etc.. But, neither from these values it coincides not with the desired instantaneous value. Through the PWM modulation utilization at the vector control, the desired condition can be obtained only for medium value of the respective variable.

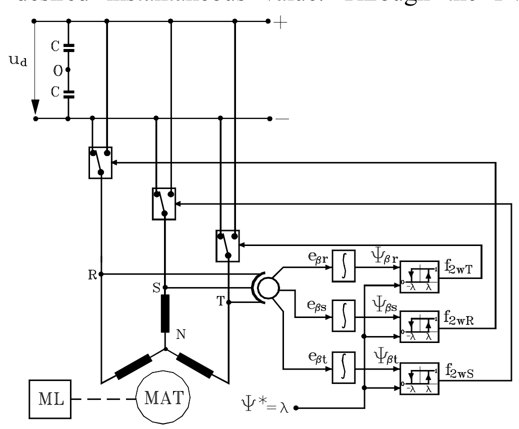


Figure 1: Principle diagram of DSC.

In the principle diagram of DSC [2] (fig.1), the close-open states of semiconductor valves can be directly controlled through the comparison of the line voltage integrals with a $\pm\psi^*$ flux reference data.

The used supplementary notations are:

$$e_{\beta r} = \frac{u_{ST}}{\sqrt{3}}; \quad e_{\beta s} = \frac{u_{TR}}{\sqrt{3}}; \quad e_{\beta t} = \frac{u_{RS}}{\sqrt{3}} \qquad (1)$$

and for integrals of these voltages they have used the notations corresponding to the ψ "flux" components on the β_r, β_s, β_t axes (fig.1), [2]. They have been used the "flux" name having on sight the modality to obtain an each component (through the integration of voltage) [2] and because in the $R_s \approx 0$ approximation case, it is obtained even the stator flux components on those reminded three axes. It is observed the correspondence between the flux components and the two-position controllers outputs, the $\psi_{\beta r}$ component establishing, through the comparing with the ψ^* reference data, the f_{2wT} switching function of T phase of the inverter. In the same way, the $\psi_{\beta s}$ component establishes the f_{2wR} function, and the $\psi_{\beta t}$ component establishes the f_{2wS} function.

2. USED MODELS IN DSC DIAGRAMS

ABB (ADTRANZ) has implemented the DSC principle successfully through the MICAS microcomputer traction control system utilization [5]. Unlike the vector control, in the implementations case on the high speed trains, the DSC diagram structure like specific feature it has three different configurations corresponding to a three stator frequency domains: $(0, f_{sN}/3]$, $(f_{sN}/3, f_{sN}]$ and $(f_{sN}, f_{smax}]$. All those three configurations have however like common elements two identical calculus blocks, corresponding to the traction induction motor and the voltage-source inverter.

2.1 Traction induction motor model

The used model in the implemented control diagrams with MICAS it has at basis the equivalent diagram of traction induction motor with the concentrated leakage

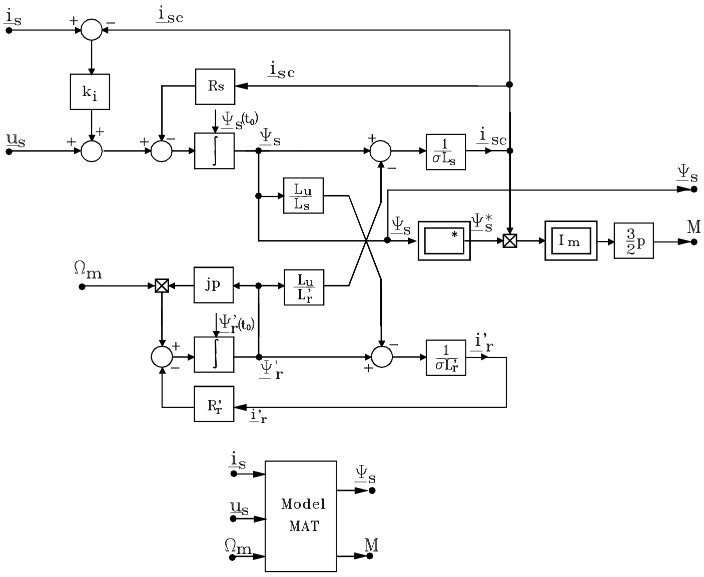


Figure 2: Traction induction motor model used in the DSC

inductivities in the rotor mesh [5], [7].

Unlike, in the paper it is presented an equivalent model, built on the mathematical model basis of the written traction induction motor electromagnetic part with space phasors in the (α,j·β) stator reference frame:

$$\underline{u}_s = R_s \cdot \underline{i}_s + \frac{d\underline{\psi}_s}{dt}; \quad 0 = R_r' \cdot \underline{i}_r' + \frac{d\underline{\psi}_r'}{dt} - j \cdot \omega_m \cdot \underline{\psi}_r'$$

$$\underline{\psi}_s = L_s \cdot \underline{i}_s + L_u \cdot \underline{i}_r'; \quad \underline{\psi}_r' = L_u \cdot \underline{i}_s + L_r' \cdot \underline{i}_r' \qquad (2)$$

$$M = \frac{3}{2} \cdot p \cdot \mathrm{Im}\{\underline{i}_s \cdot \underline{\psi}_s^*\}$$

The (2) mathematical model can be brought in the shape:

$$\frac{d\underline{\psi}_s}{dt} = \underline{u}_s - R_s \cdot \underline{i}_s; \quad \frac{d\underline{\psi}_r'}{dt} = j \cdot p \cdot \Omega_m \cdot \underline{\psi}_r' - R_r' \cdot i_r'$$

$$\underline{i}_s = \frac{\underline{\psi}_s - \frac{L_u}{L_r'} \cdot \underline{\psi}_r'}{\sigma L_s}; \quad \underline{i}_r' = \frac{\underline{\psi}_r' - \frac{L_u}{L_s} \cdot \underline{\psi}_s}{\sigma L_r'} \qquad (3)$$

$$M = \frac{3}{2} \cdot p \cdot \mathrm{Im}\{\underline{i}_s \cdot \underline{\psi}_s^*\}$$

where $\sigma = 1 - \frac{L_u^2}{L_s \cdot L_r'}$ it represents the leakage coefficient of motor.

By means of the (3) equations it is built the structural diagram and the mask block of the induction motor electromagnetic part. Moreover, through the introduction of a supplementary input variable, the obtained $\underline{i}_s$ stator current vector, which it will be compared with the $\underline{i}_{sc}$ calculated adequate value, it is obtained the used traction induction motor model in the DSC (fig.2).

For the $\underline{\psi}_s = \psi_{s\alpha} + j \cdot \psi_{s\beta}$ vector projections being, on the β_r, β_s and β_t axes they are used the calculus relations:

$$\psi_{s\beta r} = \psi_{s\beta}$$

$$\psi_{s\beta s} = -\frac{\sqrt{3}}{2} \cdot \psi_{s\alpha} - \frac{1}{2} \cdot \psi_{s\beta} \qquad (4)$$

$$\psi_{s\beta t} = \frac{\sqrt{3}}{2} \cdot \psi_{s\alpha} - \frac{1}{2} \cdot \psi_{s\beta}$$

2.2 Voltage-source inverter model

Within the framework of this model, on the $f_{2wR,S,T}$ switching functions and the voltage value basis from the DC-link circuit, must calculated the $\underline{u}_s$ supplied stator voltage vector by the voltage-source inverter (fig.3).

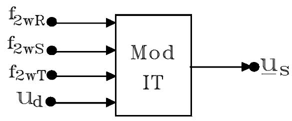


Figure 3: Voltage-source inverter model

Because when $f_{2wR} = 1 \Rightarrow u_{RO} = +\frac{u_d}{2}$ and when $f_{2wR} = 0 \Rightarrow u_{RO} = -\frac{u_d}{2}$ then it is obtained like reference:

$$u_{RO} = f_{2wR} \cdot \frac{u_d}{2} - (1 - f_{2wR}) \cdot \frac{u_d}{2} \qquad (5)$$

$$u_{RO} = (2 \cdot f_{2wR} - 1) \cdot \frac{u_d}{2}$$

Entirely alike

$$u_{SO} = (2 \cdot f_{2wS} - 1) \cdot \frac{u_d}{2} \qquad (6)$$

$$u_{TO} = (2 \cdot f_{2wT} - 1) \cdot \frac{u_d}{2}$$

Thus it results the function that it defines the block corresponding to the voltage-source inverter (fig.3)

$$\underline{u}_s = \frac{2 \cdot u_d}{3} \cdot (f_{2wR} + a \cdot f_{2wS} + a^2 \cdot f_{2wT}) \qquad (7)$$

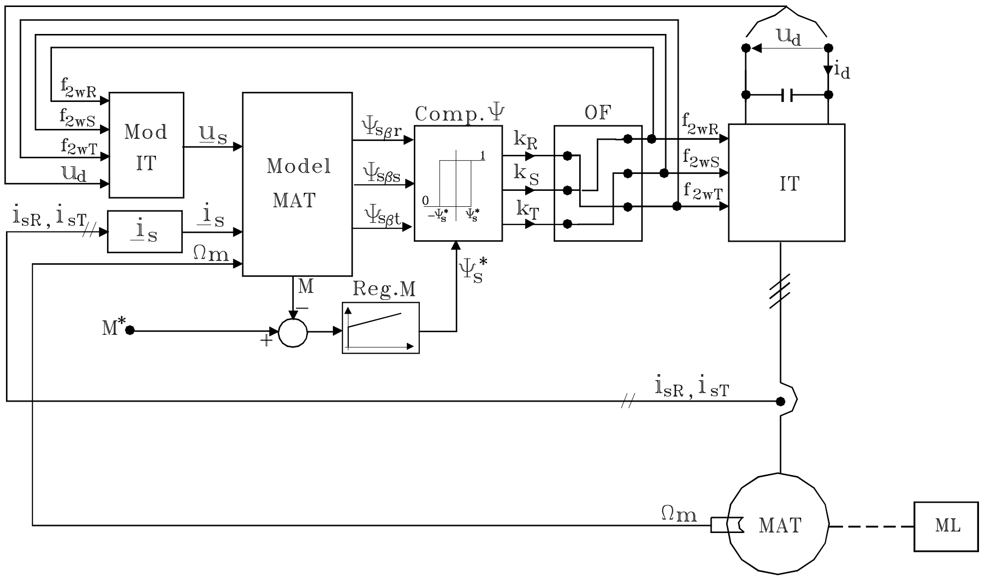


Figure 4: DSC diagram in high-speed domain

For all those three regimes, the traction induction motor will be fed from a voltage-source inverter commanded by the $f_{2wR,S,T}$ signals.
From two phases they are collected the stator currents, and through the intermediation of a speed transducer it is known the Ω_m mechanical angular speed of the motor rotor, too.
These variables together with voltage value from the DC-link circuit they are taken by the control diagram.

3. DSC IN HIGH SPEED DOMAIN

At high speed, traction induction motor is working with $U_s=U_{sN}$, $\psi_s<\psi_{sN}$, $f_s>f_{sN}$ and reference data of the ψ_s^* stator flux it is obtained at the output of the torque PI controller (fig.4).
The $\underline{i}_s$ stator current vector is calculated by means of the measured value of the i_{sR} and i_{sT} currents and from the obtained condition of an equilibrated system, too, and $\underline{u}_s$ on the previously presented inverter model basis.
Those three components of the $\underline{\psi}_s$ flux vector they are calculated with the (4) equations. Through the comparing, in the two position controller (Comp.ψ), of those three components of flux with the ψ^* reference data, they result the k_R, k_S, k_T signals. After the order of these signals in the signal select (OF), they result the $f_{2wR,S,T}$ switching functions of the voltage-source inverter.

4. DSC IN MEDIUM SPEED DOMAIN

In this working regime ($U_s<U_{sN}$, $\psi_s=\psi_{sN}$, $f_{sN}/3\leq f_s\leq f_{sN}$), the control diagram has a few modifications given the

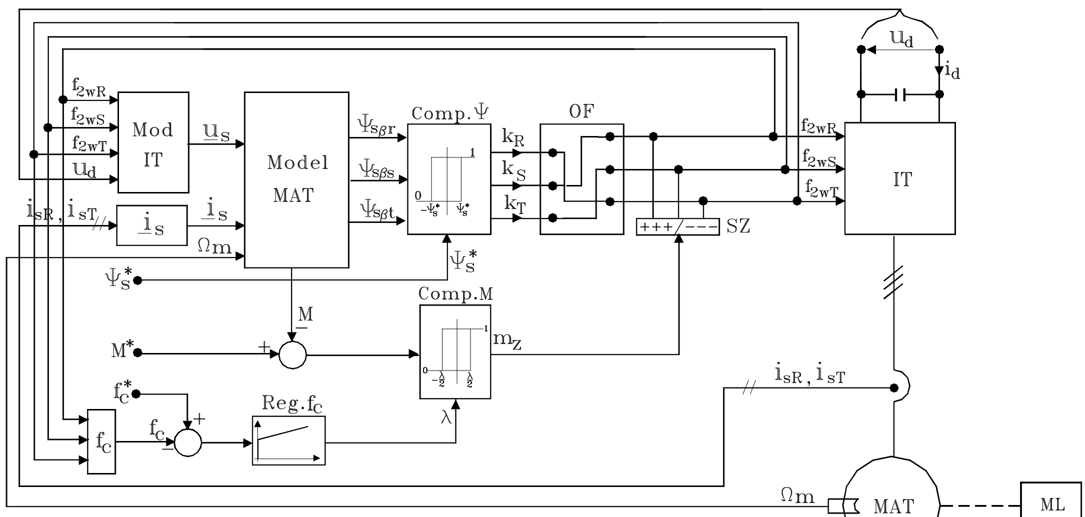


Figure 5: DSC diagram in medium speed domain

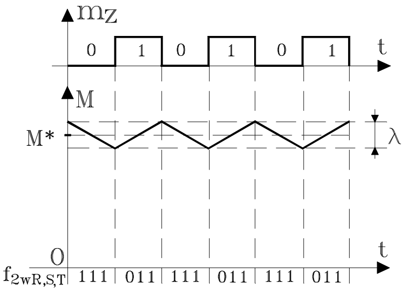


Figure 6: Diagram of m_z signal formation

previous case (fig.5):
- the reference data of ψ^* flux corresponds the rated value of the stator flux, and
- the difference between the reference data and the instantaneous value of torque it is compared in the Comp.M block (alike with Comp.ψ), having like result the m_z signal with two possibly values 0 and 1 (fig.6).

The λ variation interval width of the torque, which it characterizes the Comp.M comparing block of the torques, it is given by the switching frequency controller. This PI controller has at input the difference between the reference data of the switching frequency and the instantaneous value of the same deducted switching frequency on the $f_{2wR,S,T}$ signals basis.

The m_z signal value influences the $f_{2wR,S,T}$ signals values, thus:
- if m_z=1, then the $f_{2wR,S,T}$ signals keep them the resulted values from the OF;
- if m_z=0, then the $f_{2wR,S,T}$ signals take an imposed value by the SZ, like:

111 or 000 depending on their previous values, so that we have only a modification (for example 101 → 111 and 001 → 000) (fig.6).

Through the Comp.M block intermediation it is achieved the fastest intervention about the torque, which it is made to pulsate at nearly three times of the f_c switching frequency.

5. INDIRECT SELF CONTROL (ISC) IN LOW SPEED DOMAIN

In the low speed domain ($U_s<U_{sN}$, $\psi_s=\psi_{sN}$, $f_s<f_{sN}/3$), the control diagram presents important modifications given the previous cases (fig.7). It is observed the utilization of a different control like principle, based on the PWM modulation and named the **I**ndirect **S**elf **C**ontrol or **I**ndirect **S**tator-quantities **C**ontrol (ISC).

Those two used controllers (for torque and flux) are by P type. The used calculus relations within the framework of the controllers and new blocks are:
- for the flux controller :

$$k_{\psi s} = p_\psi \cdot \frac{\psi_s^* - \psi_s}{\psi_s^*} \quad \text{with} \quad p_\psi < 1 \tag{8}$$

- for the torque controller

$$\Delta x_d = p_M \cdot \frac{4}{3} \cdot \frac{\sigma \cdot L_s}{(1-\sigma)\cdot p} \cdot \frac{M^* - M}{\psi_s^{*2}} \quad \text{with} \quad p_M < 0{,}5 \tag{9}$$

where Δx_d it is the dynamic angular displacement of $\underline{\psi}_s$ (established by a modification of the instantaneous value of the M torque given by the M^* reference data);
- the static angular displacement of $\underline{\psi}_s$

$$\Delta x_{st} = T_p \cdot \omega_s \quad \text{with} \quad T_p = \frac{1}{2 \cdot f_c} \tag{10}$$

- the rotor angular speed

$$\omega_r = \frac{R_r' \cdot (1-\sigma)}{\sigma \cdot L_s} \cdot tg\{\frac{1}{2}\arcsin[\frac{M}{M^*} \cdot (\frac{\psi^*}{\psi_s})^2]\} \tag{11}$$

- the $\Delta\underline{\psi}_s$ variation: $\Delta\underline{\psi}_s = [e^{j\cdot\Delta x} \cdot (1 + k_{\psi s}) - 1] \cdot \underline{\psi}_s$ **(**12)

- the $\underline{u}_s$ stator voltage: $\underline{u}_s = R_s \cdot \underline{i}_s + \frac{\Delta\underline{\psi}_s}{T_p}$ (13)

In the end, within the framework of the PWM block, the $\underline{u}_s$ voltage it is decomposed in those three

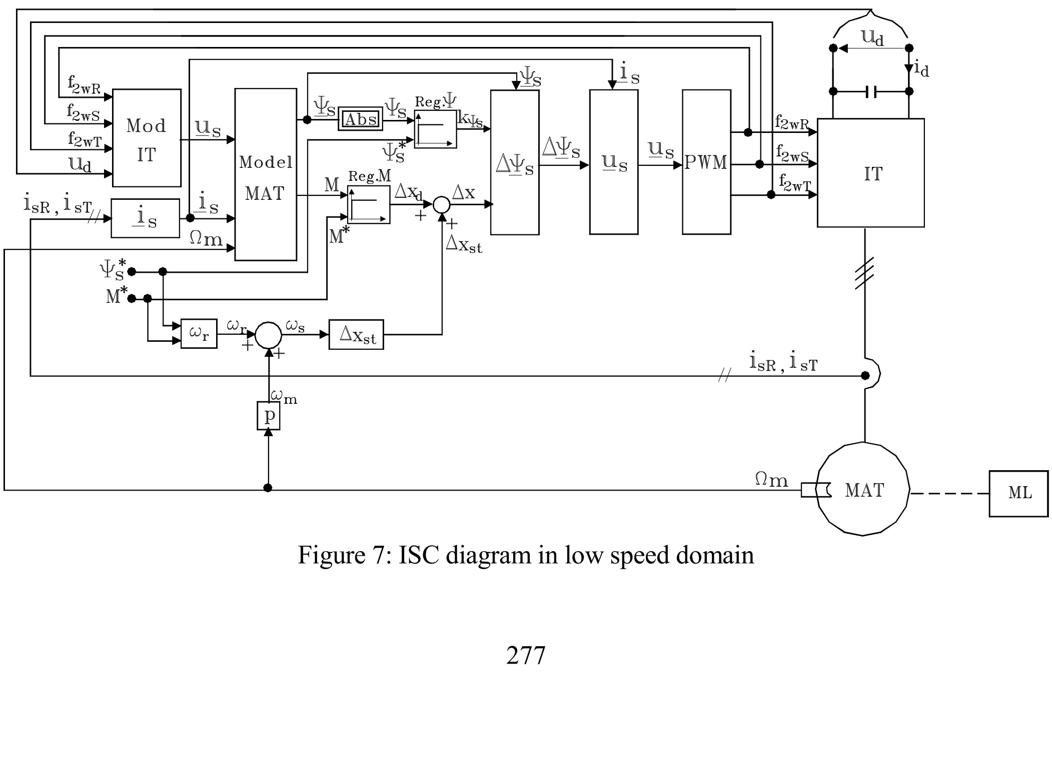


Figure 7: ISC diagram in low speed domain

components corresponding to the traction induction motor phases, compared with the triangular signal by f_c frequency, resulting thus the $f_{2wR,S,T}$ signals command of the inverter. Because of the PWM modulation, the current is very near to sinusoidal wave. Through the simple elimination of this block it is obtained a model of the ISC, which it take account only by the feeding voltage fundamental of the traction induction motor.

The success of the DSC it is coherently by the thyristors utilization in the voltage-source inverter construction and their restricted switching frequency.

The DSC, presented for the two levels voltage-source inverter utilization case, can be implemented whenever the machine converter is a three levels voltage-source inverter, too [3].

The high power IGBT appearance in traction it has imposed the utilization towards the ADTRANZ of a new control strategy based yet on the ISC [4], [7].

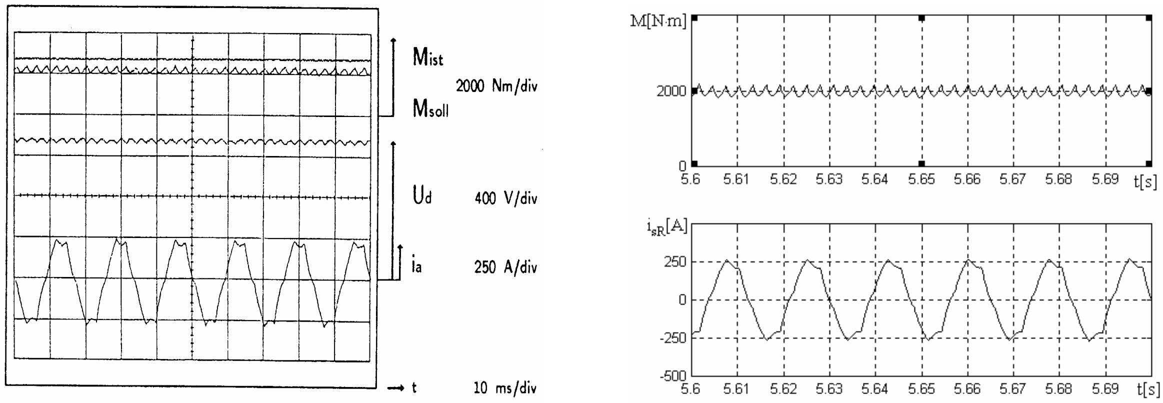
6. VALIDATION RESULTS

On the mathematical models basis associated with the DSC can be created SIMULINK models, having the same topology structure. Through adequate completions or simplifications can be achieved models which they permit the study through simulation of the different phenomenon specific to the electric traction.

A validation of the models correctness used for DSC it can make by means of the experimental results presented in [6]. In this sense it is used the DSC model, with the dates of another traction motor [6].

Further on, they are presented comparatively the obtained dates experimental way with those obtained through simulation. In the last case, it appears not the voltage variation from the intermediate circuit, too, which it has been considered in simulation, like being constant. The comparisons are given graphically, through the alike diagrams juxtaposition.

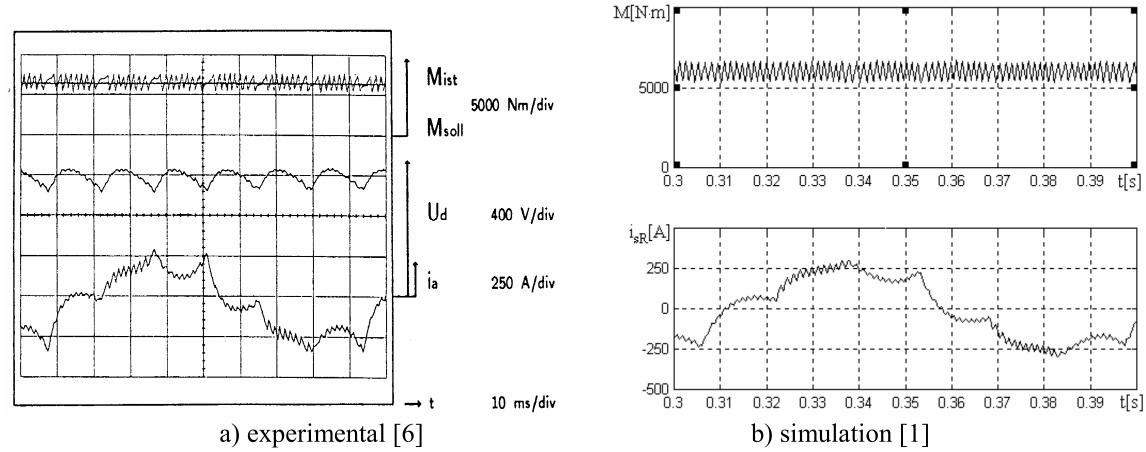
They have been compared the torque and current variations on phase of the traction induction motor in four situations:



a) experimental [6]   b) simulation [1]

Figure 8: Torque and phase current of traction induction motor at DSC in high speeds domain (DSC-W)

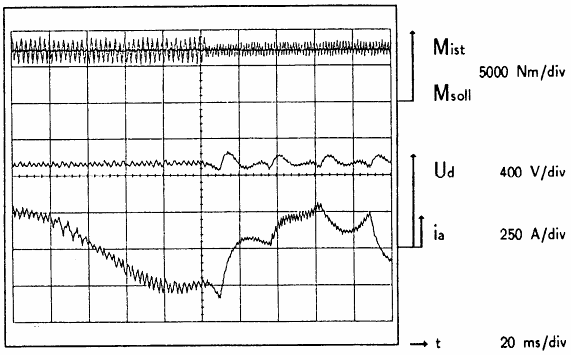
- at the DSC in the high speeds domain (DSC-W) (fig.8);
- at the DSC (fig.9);



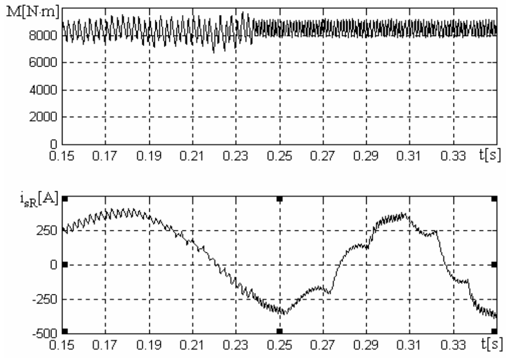
a) experimental [6]   b) simulation [1]

Figure 9: Torque and phase current of traction induction motor at DSC

- at the passing from the ISC to the DSC (fig.10);



a) experimental [6]



b) simulation [1]

Figure 10: Torque and phase current of traction induction motor at passing from ISC to DSC

The comparative analysis it underlines the elaboration correctness of the DSC specific models.

7. CONCLUSION

The used DSC on the locomotives and electric trains with traction induction motor it supposes three different configurations corresponding to a three stator frequency domains. For all these configurations they have been achieved the mathematical models of the component blocks, and they have been built structural diagrams for:
- DSC in the high-speed domain (weakening field)
- DSC in the medium speed domain
- ISC in the low speed domain.

The obtained structural diagrams permit a immediate implementation into a simulation soft like MATLAB-SIMULINK, being thus usefully at the study through simulation of phenomenon's from modern electric traction. By means of these models they have achieved simulations, which they have been, praised the specific features of this control type. Through the comparison with experimental results it has been validated the used models achievement correctness.
The introduction of structure and useful models in simulation for DSC it completes an empty in Romanian references as for this used control type on large scale in the modern electric traction.

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